Method for the measurement of anisotropy and rotational hysteresis using linear dichroism

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A technique combining x-ray magnetic linear dichroism absorption spectroscopy and rotational hysteresis loops is demonstrated. This technique, x-ray magnetic linear loops (XMLL), is used to extract magnetocrystalline anisotropy information. Results from two systems, a polycrystalline Fe film, and an epitaxial Fe film which exhibit different magnetic anisotropies, are shown. The measured XMLL is described using a simple single-domain anisotropy model. © *2001 American Institute of Physics.* [DOI: 10.1063/1.1383573]

Typically, magnetic measurements of hysteresis and magnetocrystalline anisotropy are performed using one of several bulk magnetization techniques. One method is to use a vibrating sample magnetometer.[1] A drawback to this method is that a number of measurements are needed to determine anisotropy information. Another method is to use a torque magnetometer.[1] This instrument allows direct determination of the anisotropy constants of a material. Synchrotron-based techniques have also been used. One method employed is to measure hysteresis loops in conjunction with x-ray magnetic circular dichroism in absorption (XMCD).[2] This technique, however, is limited to systems with ferromagnetic order and requires a number of measurements to determine the direction of the magnetization in the system under study.[3] A method is presented for the measurement of rotational hysteresis loops from both ferro- and antiferromagnetic materials. X-ray magnetic linear dichroism (XMLD) spectroscopy is used to monitor the absorption signal from polycrystalline Fe and an epitaxially grown Fe(001) film, yielding anisotropy information in a single measurement.[4,5]

The majority of dichroism experiments performed to date have used circularly polarized light, due to the relatively large response size of the XMCD effect ($\approx 150\,\%$ with respect to the edge jump). XMLD, on the other hand, is much weaker ($\approx 8\%$), and thus more experimentally demanding.[6] With the advent of third-generation light sources, however, this has become of less concern. With linearly polarized light, the dichroism is sensitive to the orientation of magnetic moment **M**, with respect to the polarization direction of incident x-ray field $\hat{\epsilon}$, such that $\langle(\mathbf{M}\cdot\hat{\epsilon})^2\rangle$. Thus, an XMLD spectrum is obtained by taking the difference between an absorption spectra taken with a sample's magnetization perpendicular to the polarization axis, and one that has the magnetization parallel to the axis. Van der Laan has shown that spin-orbit anisotropy information can be obtained from XMLD by application of sum rules.[7,8] However, the form of the linear dichroism response [i.e., $\langle(\mathbf{M}\cdot\hat{\epsilon})^2\rangle$] suggests a more direct way of extracting anisotropy information. To measure a x-ray magnetic linear loop (XMLL), an external field held at constant magnitude is rotated 360° in the plane of the sample. With weak anisotropy or large field magnitude, **M** will follow the applied field and the magnitude of the XMLL signal will follow $\cos 2\gamma$, where γ is the angle between **M** and $\hat{\epsilon}$. Clearly, a sample's magnetocrystalline anisotropy will cause the measured XMLL signal to deviate from this relationship. Results below on two Fe films of different crystallographic orientation and magnetic properties confirm our model.

Both films were grown using magnetron sputter deposition. The polycrystalline Fe film, grown at room temperature, had the following structure: SiN/300 Å Fe/25 Å Au. The Fe(001) film was grown according to the recipes given in Refs. 9 and 10. MgO was used for the (001) substrate, Cr buffer layers consisted of 25 Å at 600 °C, and 300 Å at 300 °C. At 200 °C an additional 25 Å of Cr was deposited, then a 157 Å Fe film was deposited. A 20 Å Si_3N_4 layer served as a cap to prevent oxidation. Magneto-optic Kerr effect (MOKE) hysteresis loops were measured on both samples to determine the bulk magnetic properties. Additionally, x-ray diffraction was used to confirm the crystallographic orientation of the (001) film.

Measurements were performed at SRI-CAT beamline 2-ID-C at the Advanced Photon Source.[11] The end station used has two integral dipole electromagnets oriented at 90° to one another. With this arrangement, it is possible to apply a field of up to 1 kOe in any direction in the plane of the sample. The field angle is calibrated from two *in situ* Hall probes. Samples are mounted normal to the incoming x-ray beam. The absorption signal is measured by monitoring the

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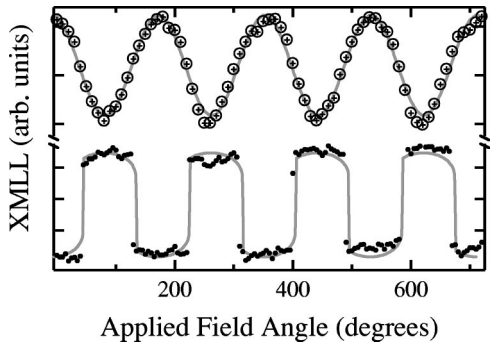

FIG. 1. X-ray magnetic linear loops vs applied-field angle for polycrystalline Fe (top, circled crosses) and Fe(001) (bottom, filled circles). Solid lines: (bottom, calculation; top, fit). Field magnitudes used were $|\mathbf{H}|=60$ Oe and $|\mathbf{H}|=45$ Oe for the Fe(001) and polycrystalline, respectively.

total drain current from the sample, total electron yield, however, detection efficiency of electrons will vary with applied field strength and direction. Two measurements are made at different photon energies in order to take detection variations into account. One measurement is made at resonance, $\sigma_r = 707$ eV, while the second is made at a photon energy well above the absorption edge, $\sigma_o = 740$ eV.[12] The magnetic contribution at resonance can be determined by normalizing the XMLL signal, i.e., σ_r/σ_o.

The XMLL measured with an applied field of $|\mathbf{H}| = 45$ Oe on the polycrystalline sample is shown in Fig. 1 as circled crosses. Note that the coercivity of the sample, H_c, is 32 Oe. The gray solid line is a fit to the data given by the relation $A\cos(2\gamma+\Phi)$. Given the weak anisotropy of the polycrystalline film, it is expected that the film magnetization will rotate coherently and track with the applied field. Given the close agreement between the fit and the data, we can infer that this is indeed the case. But, as $|\mathbf{H}|$ is reduced, the energy applied to the system is lowered such that a change in both magnitude A and phase lag Φ should be observed. To examine the form of A and Φ, a number of XMLL curves were taken using different $|\mathbf{H}|$. From the fits of these curves, A and Φ were determined (shown in Fig. 2).

The XMLL amplitude as a function of $|\mathbf{H}|$ is shown at the top of Fig. 2. Due to the polycrystalline structure of the sample, it is expected that changes in the magnetization state will be dominated by domain-wall motion. Thus, the decrease of the amplitude is assumed to be exponential. The solid line in Fig. 2 is an exponential fit showing good agreement. Phase lag Φ is shown at the bottom of Fig. 2. Recalling that $H_c = 32$ Oe, we see that the phase lag increases quite rapidly for $|\mathbf{H}|$ around this value. For smaller applied field magnitudes, less energy is applied to the system, and thus the magnetization increasingly lags the applied field. The solid line in Fig. 2 shows an exponential fit to the data.

The XMLL data from the Fe(001) film is shown at the bottom of Fig. 1 by filled circles. An applied field angle of 0° corresponds to the Fe[100] direction and the direction of $\hat{\epsilon}$. From MOKE loops taken on the sample, the [100] is along the easy-magnetization axis and the sample anisotropy is fourfold. Clearly, the stronger magnetocrystalline anisotropy influences the shape of the XMLL. While the XMLL still varies as $\cos 2\gamma$, the transition across a hard axis is more abrupt than that seen in the weak anisotropy (polycrystalline)

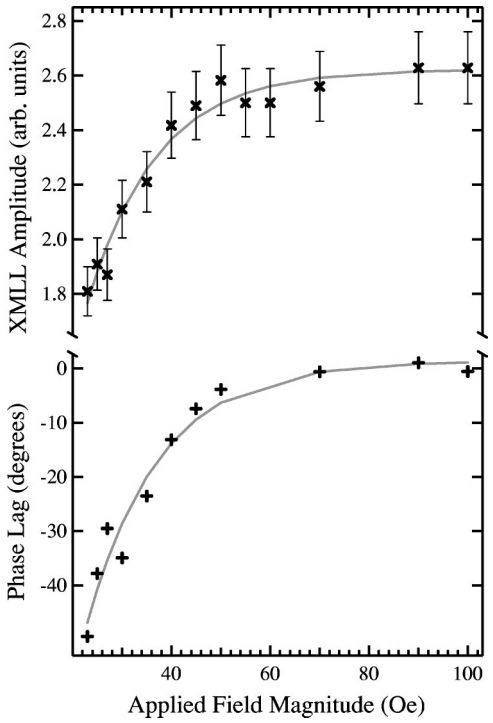

FIG. 2. XMLL amplitude and phase lag vs $|\mathbf{H}|$ for polycrystalline Fe.

case. Such behavior indicates that, as the applied field rotates, the magnetization "jumps" from one easy axis to the next.

To investigate this behavior further, a simple model of the system is presented and discussed. We assume that the sample contains a single magnetic domain, the moment of which rotates coherently and exhibits fourfold anisotropy. Furthermore, we assume the moment remains in plane, and ignoring higher-order anisotropy terms, the total energy of the system is then given as[13]

$$E = \frac{K_1}{4}(1-\cos 4\gamma) - HM_s\cos\theta.$$

Here, K_1 is the magnetocrystalline anisotropy constant, θ is the angle between the applied field and the magnetization, H is the magnitude of the applied field, M_s is the saturation magnetization, and as used above, γ is the angle between the magnetization and $\hat{\epsilon}$. Additionally, we define $\gamma = \phi - \theta$, where ϕ is the angle of the applied field with respect to $\hat{\epsilon}$. To simulate a XMLL experiment, the applied field is rotated by changing the angle ϕ, while keeping H constant. At each value of ϕ, the energy equation above is minimized to obtain γ. The XMLL signal is then given by $\cos 2\gamma$. Results are shown as the solid line at the bottom of Fig. 1. The calculated curve has been scaled linearly to match the magnitude of the experimental XMLL signal.

Agreement is close between calculation and experiment. It is energetically unfavorable for the magnetization to be aligned along the hard axis of the sample. In our model, γ is determined from the angle of an energy minimum. As the applied field is rotated (i.e., ϕ is changed), the angle of this minimum will follow. However, as ϕ crosses a hard axis, the angle of the energy minimum abruptly changes. We thus conclude that it is this abrupt change in the angle of the energy minimum that is the cause of the step observed in the simu-

lated XMLL. Finally, it can be concluded that the step in the experimental data is due to the magnetic moment switching from an easy axis parallel to $\hat{\epsilon}$ to another easy axis perpendicular to $\hat{\epsilon}$.

The above results concentrate on systems with only one ferromagnetic element. Most magnetic devices, however, consist of many interacting layers. The elemental specificity of XMLD, and thus XMLL, suggests further experiments with devices. For example, XMLL can be used to determine coupling behavior between different layers in a multilayer film.

A technique using x-ray magnetic linear dichroism in absorption has been demonstrated using rotational hysteresis loops. XMLD spectroscopy is indeed sensitive to the relative alignment of the sample magnetization and the x-ray polarization axis. For the weak anisotropy case of polycrystalline Fe, the XMLL signal follows a $\cos 2\gamma$ relation. In the fourfold anisotropy case of Fe(001), the XMLL follows a step function behavior. An interpretation of this behavior, using a simple single-domain anisotropy model, is presented.

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